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This paper highlights recent advances in the development of photonic transport networks. The requirements of future networks are discussed and the photonic network envisaged is identified. The role of photonic technologies in enhancing network performance is elucidated. The attributes of the new optical layer, in terms of transport layer architecture, and function allocation are discussed. The IP backbone network based on optical path technologies is highlighted. Some cutting-edge technologies, such as supercontinuum light sources and a coherent optical amplifier, are demonstrated.

Keywords: photonic network; WDM; IP backbone; photonic technologies; optical path; optical layer

1. Introduction

The recent explosion in Internet traffic implies the dawn of the multimedia age. PC penetration throughout the world is now very intense, although the degree and the time frame differ for each country. In Japan, the number of PCs has been increasing very rapidly since 1995 and Internet traffic is growing accordingly, as shown in figure 1. In North America, data traffic exceeded telephone traffic a couple of years ago, and this will become true in Japan within a few years. After that time data traffic will dominate.

This trend in communication can be expressed as a 'paradigm shift': from a voice network to a data-centric network. Means of communication are thus changing from person-to-person telephone conversation to person-to-computer or computer-to-computer communication. Accordingly, the demands made on the communication networks are changing. The existing telecommunications network should evolve to match the paradigm shift. This paper discusses how photonic network technologies (Sato 1996) will impact the creation of future bandwidth-abundant multimedia networks.

The current communication environment and the trends in transport technology will be briefly reviewed first. The important features of the photonic transport network will be addressed. The target photonic transport network and its attributes will be clarified next. The application of photonic network technologies to develop IP backbone networks will be then highlighted. The cutting-edge technologies that have been developed recently and that will enable another performance enhancement will also be described in this paper.

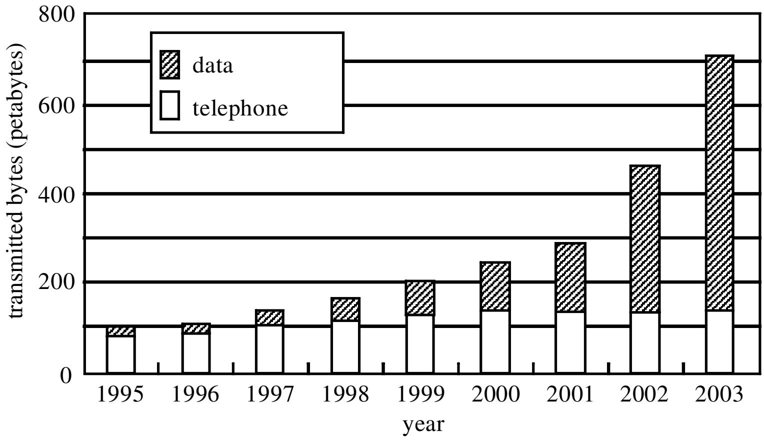

Figure 1. Statistics on telephone and data communication in Japan.

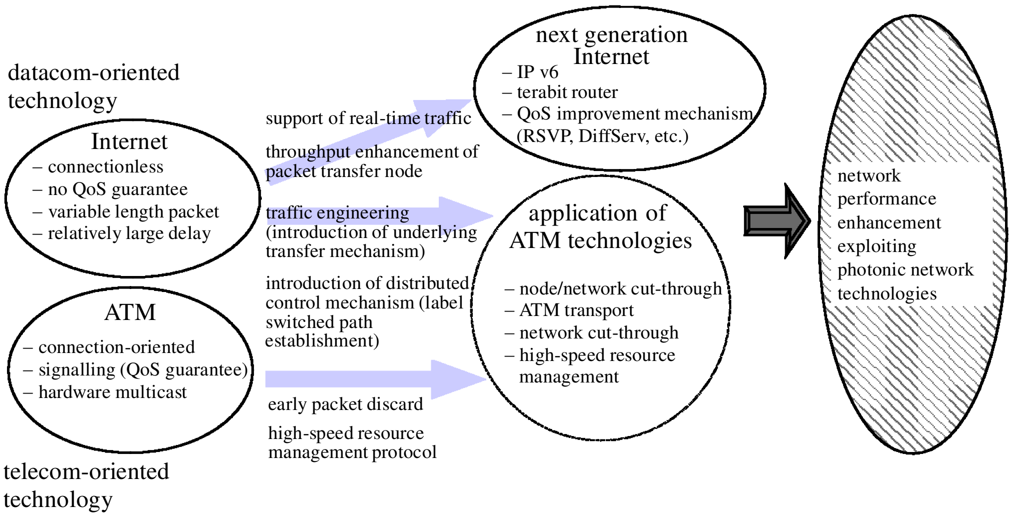

Figure 2. Enhancement of IP services with photonic technologies.

2. Enhancement of IP services

The current development activities toward data-centric networks are depicted in figure 2. Internet traffic is increasing rapidly, but the existing Internet is weak for some applications: Quality of Service (QoS) is not guaranteed, and there are difficulties in traffic engineering, increased delays due to multiple hops through routers, and insufficient router throughput.

Teleco's have been developing ATM technologies as the basis on which future multimedia networks will be built. ATM is connection-oriented, so QoS can be guaranteed, and hardware multicast can be easily implemented. On the other hand, the small size of the ATM cell causes processing bottlenecks in cell segmentation and reassembly. The highest interface bit rate available for ATM is now limited to 2.5 Gb s^{-1}.

There are two major types of network developments. One is the next generation Internet that extends existing Internet technologies. It will use IP version 6, terabit

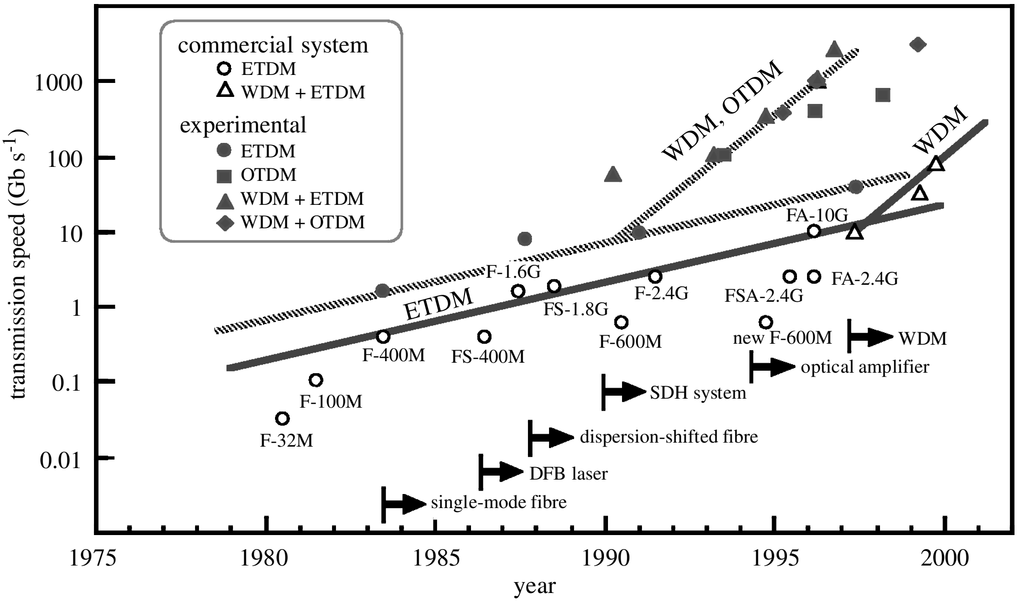

Figure 3. Transmission speed increase.

routers, and some QoS improvement mechanisms such as RSVP and DiffServ. The other applies ATM technologies or multiprotocol label switching (MPLS) technologies as the underlining transfer mechanism and will resolve the problems seen with the current Internet. This paper will discuss the next step in network development (see figure 2); the use of photonic network technologies.

3. Photonic technologies

Optical fibre has enormous low-loss bandwidth, more than 40 THz. Very high bit-rate transmission is also possible. Wavelength division multiplexing (WDM) allows the simultaneous transmission of different format signals in one fibre. Not only transmission, but also routing is possible by using the wavelength as a label. This is possible with the passive optical devices, such as the arrayed waveguide gratings, that will be mentioned later. Each optical fibre can create a communication space and a bundle of thin optical fibres can carry an enormous amount of communication traffic. Using the wave nature of light, two-dimensional optical processing is possible, and, by using well-collimated optical beams and the straight propagation paths of light in free space, three-dimensional very dense optical connections will become available.

Figure 3 shows the evolution of NTT's transport network speed. Optical fibre transmission was first introduced in 1981 and since then the transmission capacity has been increased by more than one order of magnitude per decade. In fact, 2.5 Gb s^{-1} transmission systems were introduced in Japan in 1990 and 10 Gb s^{-1} transmission systems in 1996. This resulted in a tremendous reduction in the cost of transmission. In 1989, a unique network–node interface (NNI) for synchronous digital hierarchy (SDH) was standardized in ITU-T. Two SDH paths—1.5 Mb s^{-1} and 52 Mb s^{-1}—were introduced in Japan. The introduction of SDH has simplified the existing plesiochronous digital hierarchy (PDH) path networks and allowed the

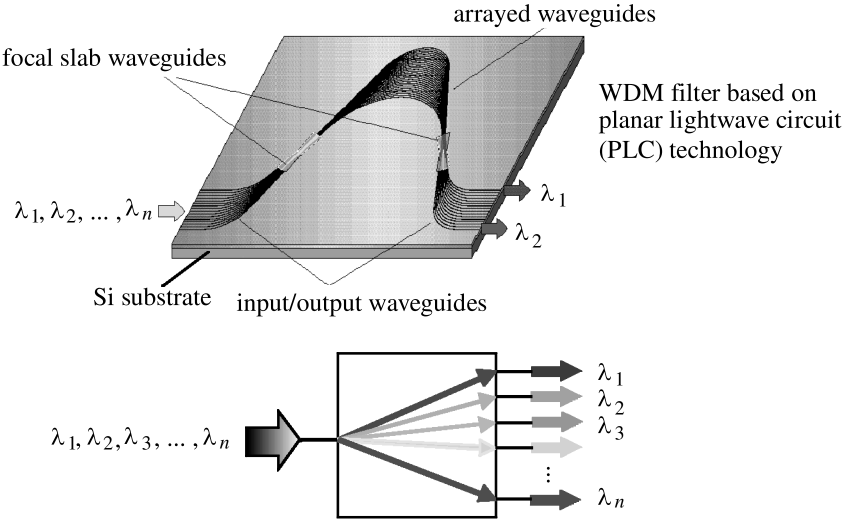

Figure 4. Arrayed-wavelength grating (AWG) multi/demultiplexer.

direct multiplexing of paths. This permits the digital cross-connect function and transmission signal monitoring capabilities to be easily implemented. The last few years have seen another leap forward in transfer mode technology, ATM. For ATM networks, the virtual path (VP) (Sato *et al*. 1990) was standardized in 1990. The VP strategy enables the fully logical realization of path functions and can greatly enhance network capability through its flexibility.

The recent notable progress in transmission is WDM, which yielded a much larger increase in transmission capacity than is possible with time division multiplexing (TDM). One important point to note here is that optical technologies have achieved tremendous transmission cost reductions, but benefits are confined to simple point-to-point transmission. Existing path technologies, or networking technologies, are based on electrical processing.

Optical transmission systems have tremendous effectiveness; however, few functions were initially available. The major available functions were the electrical-to-optical converter, laser diodes, optical fibre, the optical-to-electrical converter, and photodiodes. Very recently, a powerful new device, the optical amplifier, was introduced. It not only increased the application extent of existing point-to-point optical transmission systems, but it further extended the application of optical technologies to networking. Even though optical technologies were first introduced to our network 20 years ago, the new functions of wavelength multiplexing and demultiplexing have only recently been introduced to enhance system performance.

Figure 4 shows an example of the key component of WDM; an arrayed-waveguide grating multiplexer/demultiplexer. It is an integrated optical filter fabricated by planar lightwave circuit (PLC) technologies (Kawachi 1996), which have been well developed by NTT. An arrayed-wavelength grating (AWG) can multiplex and demultiplex multi-wavelength optical signals. It can offer 25 GHz optical frequency channel spacing (0.2 nm wavelength channel spacing) with 128 wavelength channels with fibre-to-fibre loss of *ca.* 5 dB.

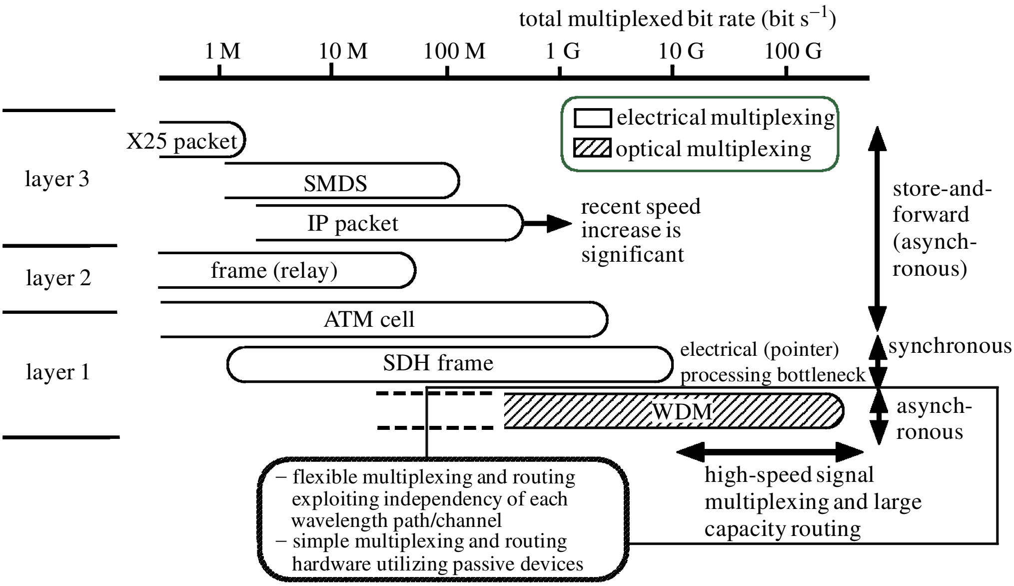

Figure 5. Duplication of multiplexing functions.

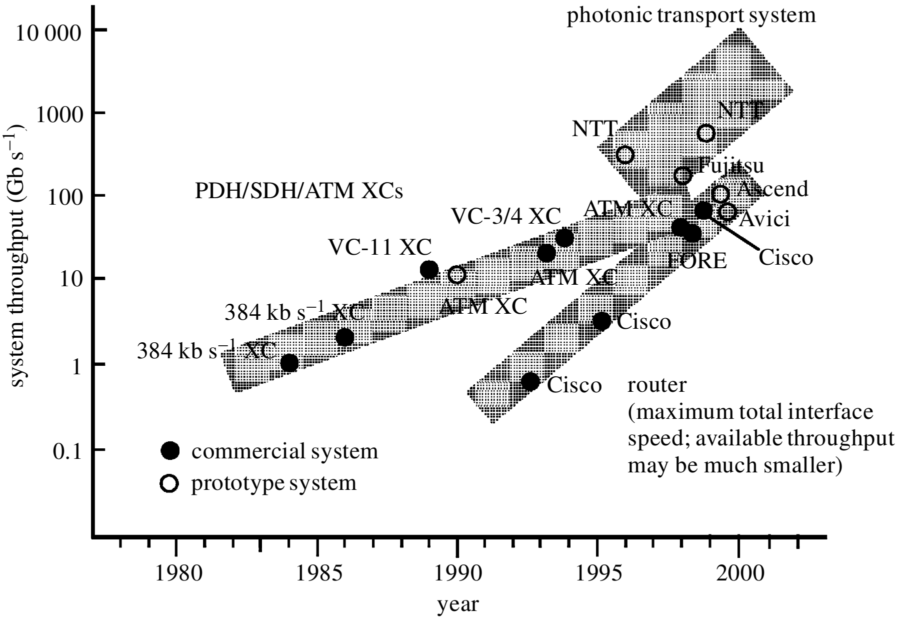

Figure 6. Node throughput enhancement with wavelength routing.

(*a*) *Duplication of multiplexing functions*

The techniques mentioned above are very effective; however, further advances will be realized by applying photonic technologies. How photonic network technologies will impact the future network is explained. Some fundamental transport network functions are first discussed. Figure 5 shows the relations between different TDM mul-

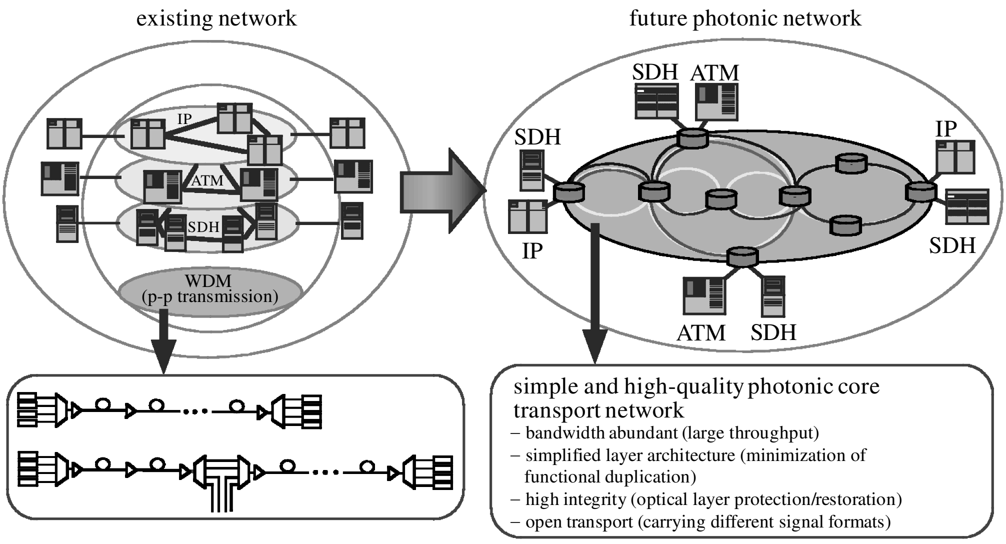

Figure 7. Photonic transport network.

tiplexing schemes and the total multiplexed bit rates, for the X.25 packet, switched multi-megabit data service packet, and IP packet in layer 3, frame (relay) in layer 2, ATM cell in layer 1/2, and SDH scheme in layer 1. Very recently, WDM has started to be used in the high-speed region. The total capacity offered by WDM is increasing continuously, so the benefit of WDM in this high-speed range is obvious. The important devices to enhance our applications from point-to-point transmission to photonic networking are space division switches and wavelength conversion functions. The effectiveness of wavelength routing is discussed hereafter.

(*b*) *Routing function*

Different routing mechanisms are used for the different multiplexing schemes. The routing entities in layers 3 and 2 are identified by the packet/cell header attached to each packet/cell, and time position in the TDM frame for SDH/PDH in layer 1. In WDM, on the other hand, wavelengths are used for routing control. The characteristics of wavelength routing are

(1) simple hardware routing that enables large routing node throughput;

(2) store-&-forward routing, which is very difficult due to lack of efficient optical memory; and

(3) routing in new dimension (wavelength), which supports different format signals.

By exploiting optical technologies, photonic transport systems can be realized that offer large throughput using devices with low power consumption.

Figure 6 shows the advances in transport node or cross-connect node throughput in NTT's networks. Cross-connect systems were first put into commercial use by NTT in 1980 for the PDH network. They employ DS2 (6.3 Mb s^{-1}) interfaces with line facilities, and the unit of cross-connection with time slot interchange techniques

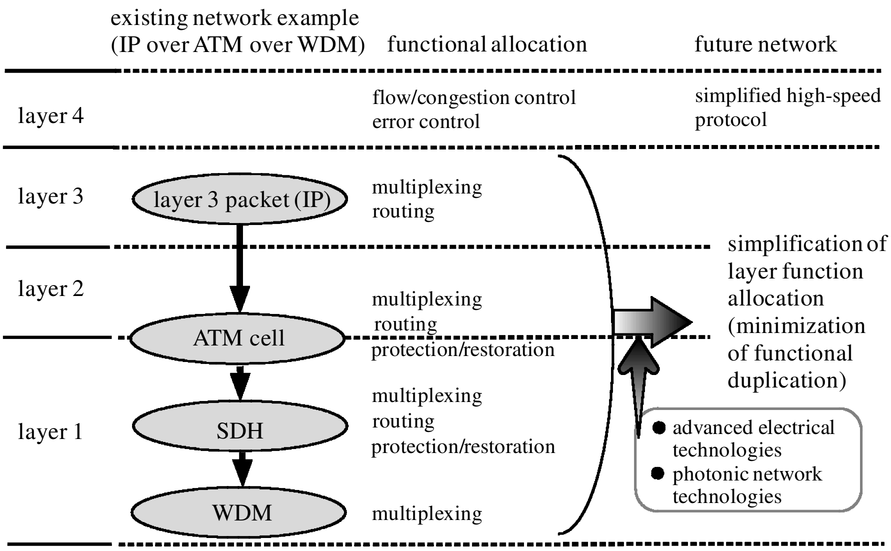

Figure 8. Functional duplications.

is 384 kb s^{-1}, or six telephone channels. The throughput of the cross-connect system has been increasing in line with the introduction of SDH in 1989 and ATM in 1994. The throughput increase factor is about 60 times per decade. The throughput increase offered by the latest IP routers is significant. They now reach the existing transport node throughput, but such routers have difficulty in offering the completely non-blocking characteristic available in existing transport systems. Photonic transport nodes that use WDM and wavelength routing can offer much larger throughput as shown in figure 6, although the path granularity may not be as fine as that of electrical systems.

4. New network paradigm

Existing networks and our envisaged future transport network that exploits photonic network technologies are compared in figure 7. There are two points to the new network paradigm. One is the separation of core and edge functions: the core network provides abundant transmission capacity with large throughput optical nodes. The electrical processing nodes, which lie in the edge network, will be connected with direct optical paths. The other is the simplification of layer structure in the core networks; different format signals are (directly) accommodated within the optical layer, which will be elaborated upon later. The core network will also ensure high integrity with optical path protection–restoration capability. Of course the core network will not be constructed overnight, and will be implemented by overlaying existing networks. Growth will come as new services are introduced.

The underlying concept of the envisaged networks is clarified by investigating the problems of existing networks. Figure 8 shows an example of the functional duplication in terms of IP packet transportation. Multiple-layer entities are used as shown in figure 8, and some of the functions in each layer are duplicated; each layer has multiplexing functions and some have routing functions and protection and/or restoration functions. Not only duplication, but also collision may occur among different layers in

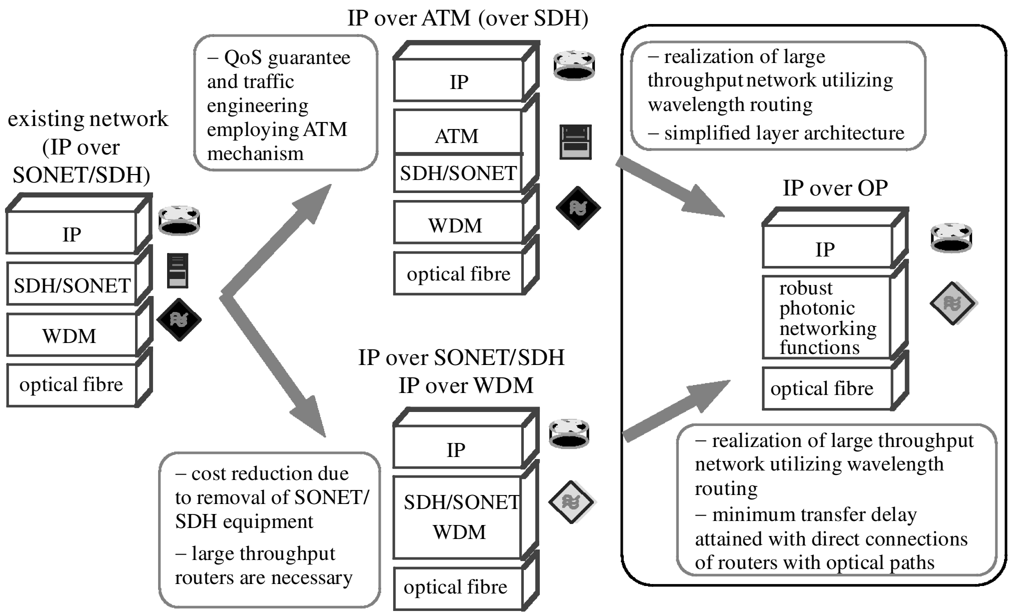

Figure 9. IP backbone network layer architecture.

terms of network protection against failures. Simplification of the network layer relation and minimization of functional duplication are very important to realize effective core networks. This will be possible by exploiting photonic network technologies.

For IP services, different technologies such as IP over ATM over SDH/SONET (synchronous digital hierarchy/synchronous optical network) over WDM, or IP over SDH/SONET over WDM have been developed. With TDM technologies, signal mapping relations tend to be complicated and a lot of standardization effort is required to specify them, which often delays service provisioning. In WDM-based photonic networks, several different electrical signal formats should be accommodated in the optical layer and each transmission format carried directly via a single optical fibre network through wavelength assignment, as an extreme case. The benefits of this approach are: new services can be introduced with minimum delay, and improved ease in upgrading network functionality (Sato & Okamoto 1999).

Figure 9 illustrates the different types of IP backbone network architectures and their technologies. IP over optical paths will be effective, especially for creating very-large-bandwidth backbone networks.

(*a*) *Node throughput enhancement*

The benefit of wavelength routing regarding node throughput is explained in figure 10. Figure 10 compares IP over SONET/SDN (over WDM) and IP over optical paths. Applying optical paths provides another level of routing that is not packet-by-packet routing, as well as a network restoration mechanism. Pass-through traffic will be self-routed at the optical level so the termination and routing of IP traffic is minimized. This scheme will be very effective in developing robust and large-bandwidth networks. Figure 10 shows the degree of node throughput enhancement possible with a photonic transport system. The cluster efficiency of IP routers is parametrized. If

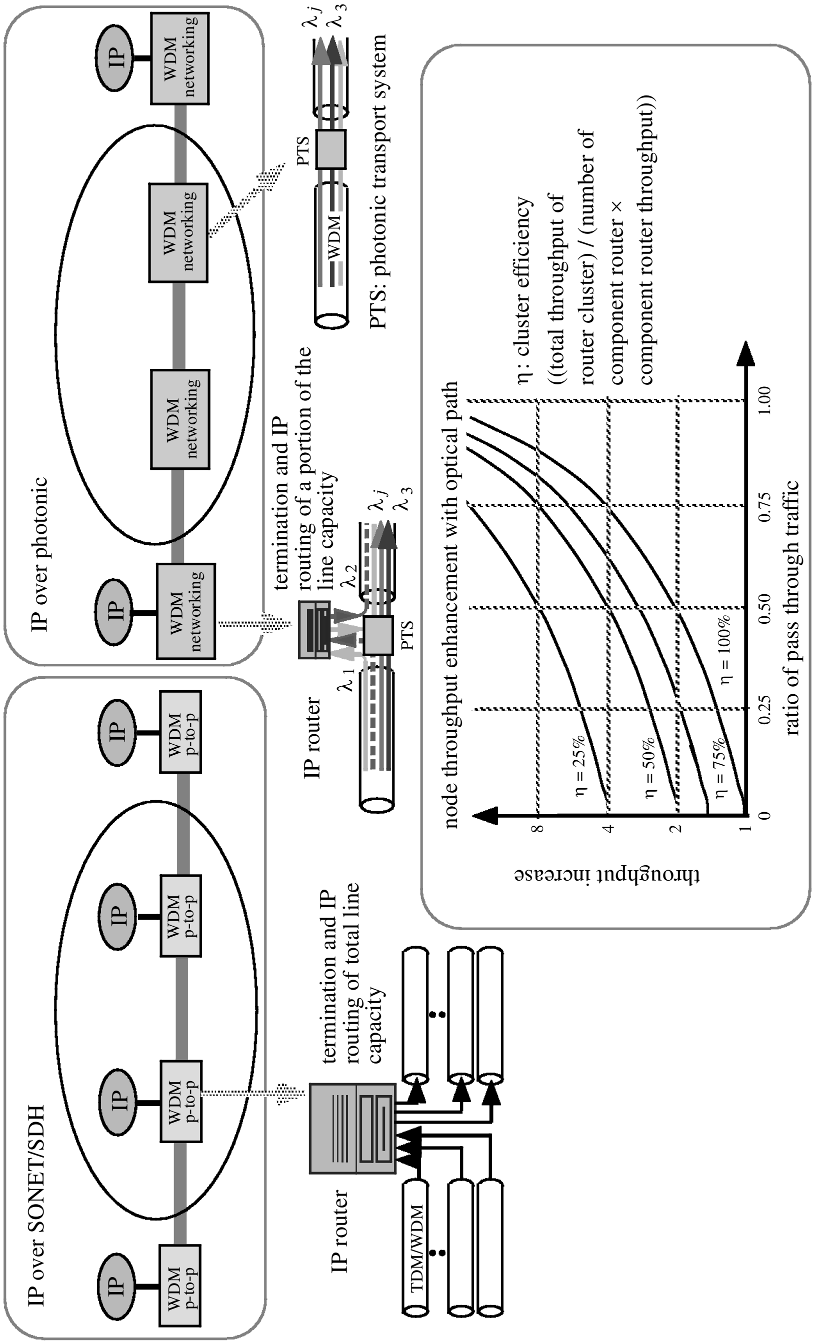

Figure 10. Node throughput enhancement with wavelength routing.

the efficiency is 50%, and the ratio of pass-through traffic is 0.5, the application of photonic transport system (PTS) (Koga *et al.* 1998) quadruples node throughput. Generally speaking, cluster efficiency decreases as the number of component IP

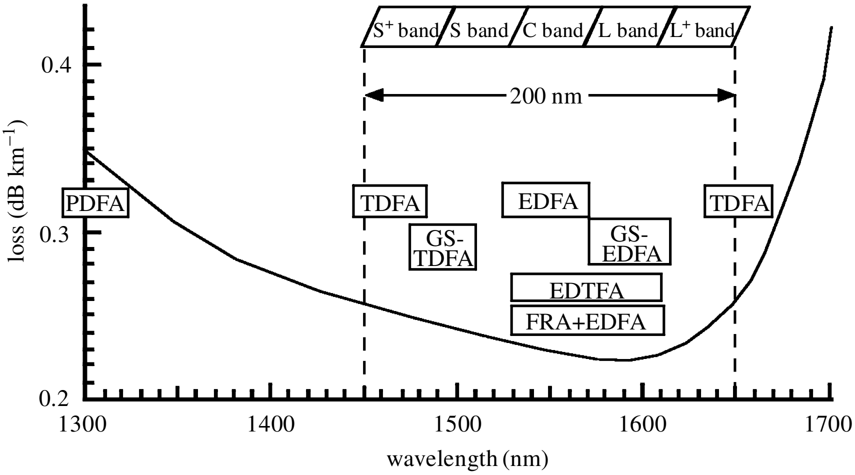

Figure 11. Optical amplifier technologies. TDFA, thulium-doped fibre amplifier; GS-TDFA, gain-shifted TDFA; EDFA, erbium-doped fibre amplifier; GS-EDFA, gain-shifted EDFA; EDTFA, telluride-based EDFA; FRA + EDFA, fibre Raman amplifier and EDFA.

routers increases, and the effectiveness of PTS will be significant particularly when designing large-throughput networks (Watanabe *et al*. 1999).

5. Cutting-edge photonic technologies

(*a*) *Optical amplifiers*

As mentioned before, we have a very wide wavelength resource (see figure 11) and if we can fully use the 200 nm bandwidth, more than 1000 wavelength channels will become available. Figure 11 lists the state-of-the-art optical amplifiers now available. These amplifiers are essential devices to enhance network performance. 'Raman amplifier' technologies are now being intensively studied.

Figure 12 shows a schematic of the distributed Raman amplifier (Masuda *et al*. 1998). In the Raman amplifier, the transmission fibres themselves become the amplification medium. So transmission line loss can be compensated, which means that fibre nonlinear effects can be suppressed. This is because the input power of the optical signal can be kept low enough to make the nonlinear effect insignificant. Another important benefit of the Raman amplifier is that it can cover the entire wavelength range.

(*b*) *Cost-effective large-capacity transmission*

Figure 13 shows the evolution in channel speed and transmission capacity. The bottom left of the chart locates the systems that are now commercially available. Other plots are experimental systems. To increase the total transmission capacity, it is obvious that we should increase TDM channel speed and the number of WDM channels. Technology developments toward this are underway and the highest TDM channel speed attained thus far is 640 Gb s^{-1}. The maximum transmission capacity attained is 3 Tb s^{-1} formed by 19 WDM channels each offering 160 Gb s^{-1} (Kawanishi *et al*. 1999). Our next commercial system should offer terabit capacity.

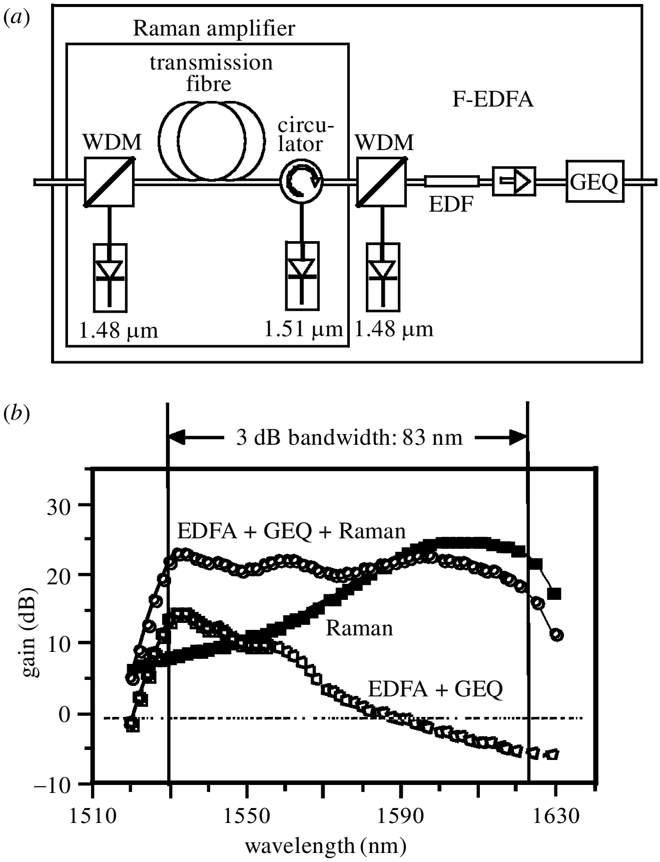

Figure 12. Distributed Raman amplifier (DRA) + EDFA. (*a*) Configuration of hybrid amplifier. (*b*) Gain spectra.

The highest TDM bit rate that is commercially available is 10 Gb s^{-1}. WDM is the key to realizing high transmission capacity; however, to attain very large capacity that approaches 1 Tbit s^{-1}, a huge number of wavelength-stabilized optical sources are required. This problem must be resolved if we are to realize the cost-effectiveness of WDM. Increasing the speed of each TDM channel is one important solution. Another is to develop totally different optical sources that can generate multiple wavelengths at the same time. We are very keen on this approach, and have been exploring various methods. If copies of an original short optical pulse can be generated simultaneously, and each has a different colour, then, that can be very useful. Recently, we succeeded in realizing this kind of technology as explained below.

(*c*) *Multi-wavelength pulse generation with SC optical source*

The technology called supercontinuum was developed, which uses the nonlinear effect of optical fibres. The spectrum of the input seed pulses, which have a narrow wavelength spectrum, is broadened when they traverse the specially designed nonlinear fibre, and when they pass through a wavelength filter such as the AWG explained before, multi-colour pulses are generated simultaneously (Morioka *et al.*

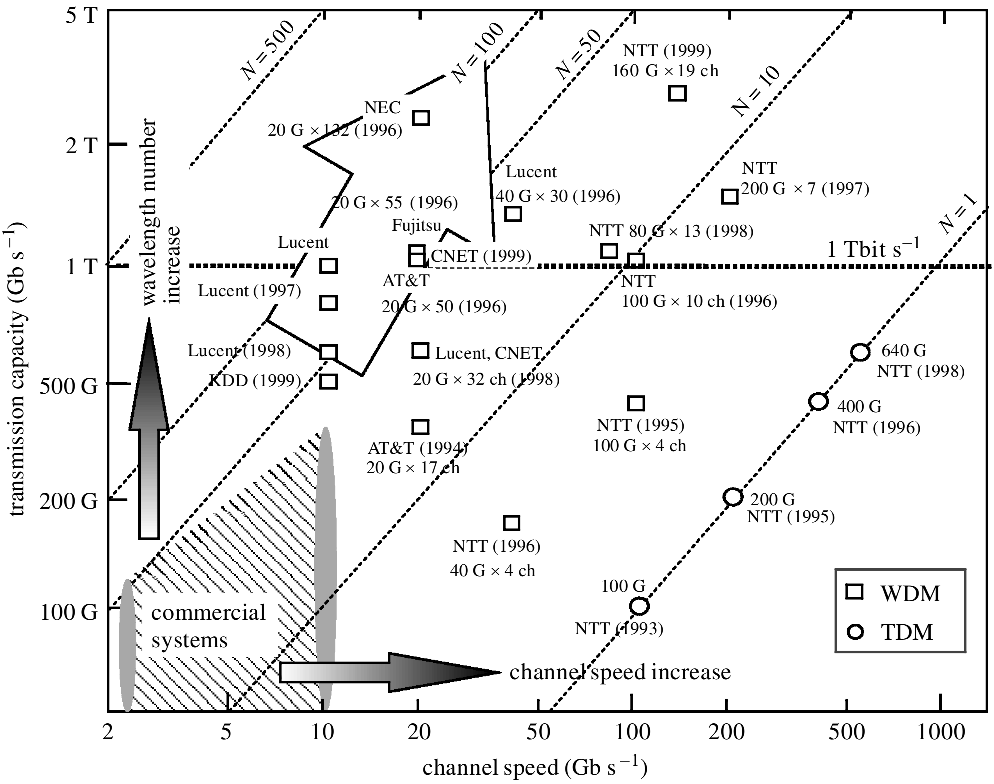

Figure 13. Evolution of high-speed and large capacity transmission.

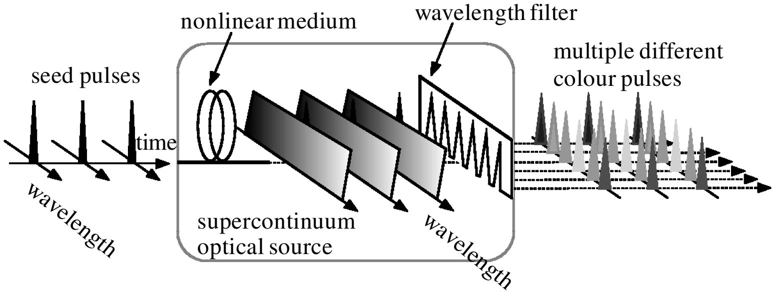

Figure 14. Multi-wavelength pulse generation with SC optical source.

1994). This is depicted in figure 14. It is relatively easy to stabilize the wavelength of one optical source, and the wavelength stability of the generated multi-colour pulses is determined by that of the wavelength filter. The stability of passive wavelength filters is one order of magnitude higher than that of active optical sources like laser diodes. Figure 15 shows the mechanism of supercontinuum generation in an optical fibre (Mori *et al*. 1997). The inset on the right-hand side shows the dispersion change along the fibre length where the dispersion gradually changes from positive to negative and L_0 is the fibre length at which dispersion becomes zero. As shown in the top figure, the input pump pulse is compressed through so-called adiabatic soliton compression in the positive (anomalous) dispersion region, resulting in the

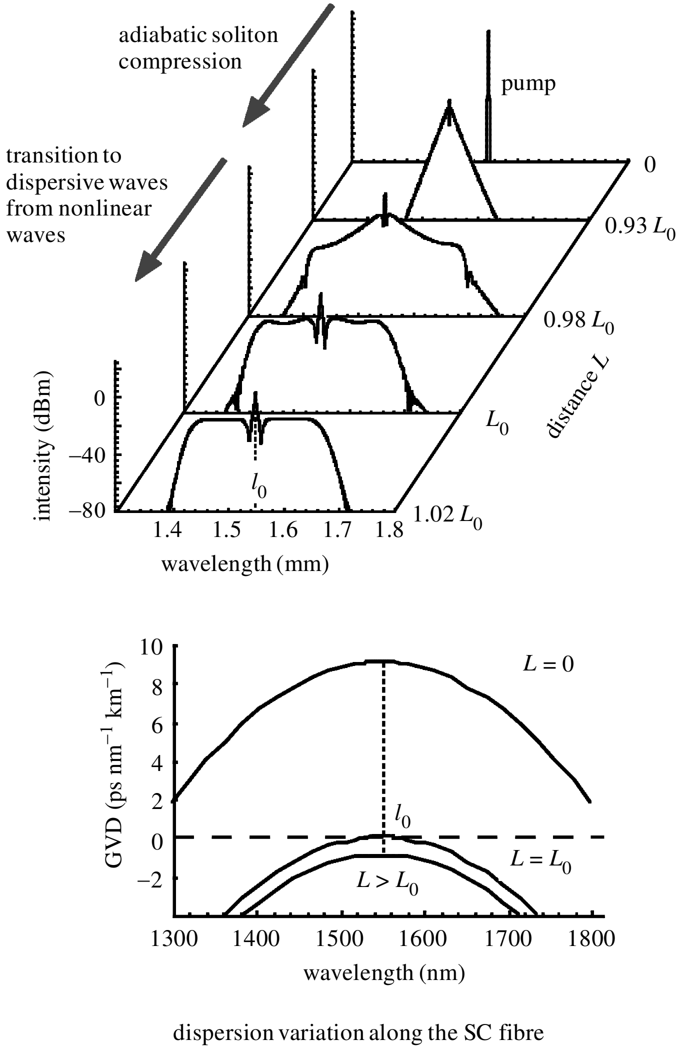

Figure 15. Mechanism of supercontinuum sources. L_0 is the effective length (the fibre length at which the maximum of the convex dispersion curve reaches zero).

super-broadened spectrum (200 times wider than the input spectrum). The supercontinuum spectrum is then reshaped (flattened) by the use of the negative dispersion, producing a top-flattened super-wide-band spectrum.

Figure 16 depicts a 3 Tbit s^{-1} transmission experiment using supercontinuum optical sources (Kawanishi *et al*. 1999). Nineteen wavelength pulses of 160 Gb s^{-1} each were generated from a supercontinuum pulse source. The results confirmed the high quality of the supercontinuum pulses.

(*d*) *Coherent optical amplifier (parametric amplifiers)*

Last, but not least, another breakthrough technology for optical amplifiers is demonstrated; the coherent optical amplifier (Caves 1982). Figure 17 shows the per-

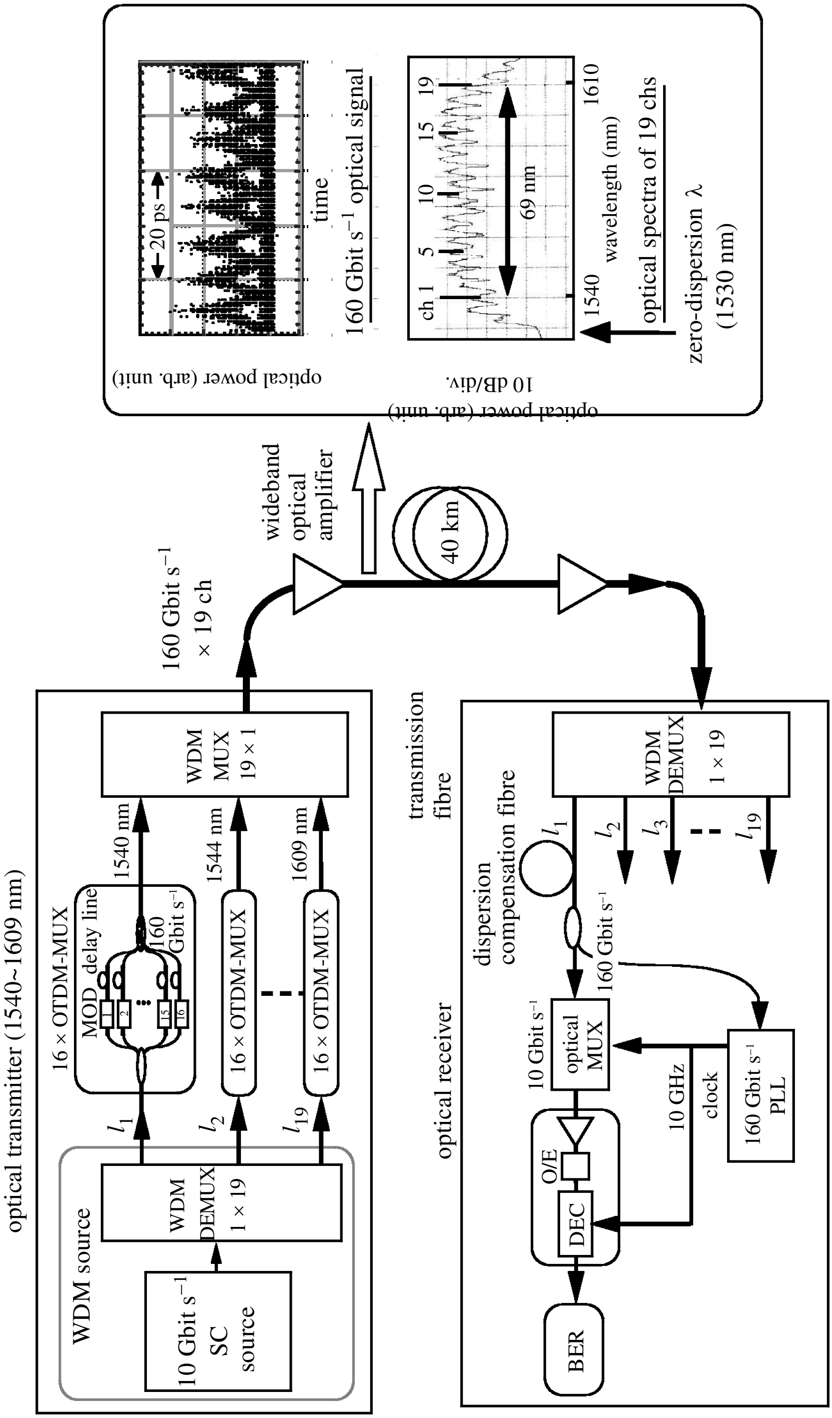

Figure 16. A 3 Tbit s^{-1} OTDM/WDM transmission experiment.

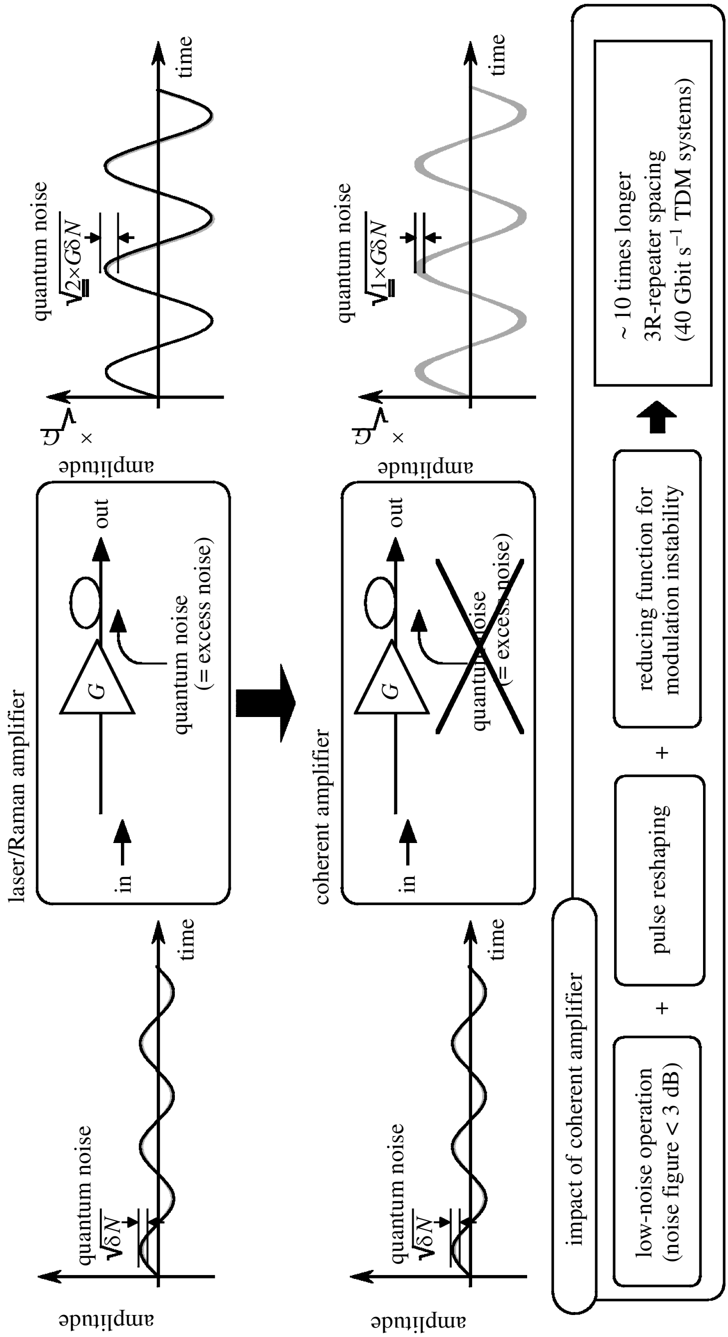

Figure 17. Coherent optical amplifier (parametric amplification).

formance difference between an ordinary Er^{3+}-doped fibre amplifier (EDFA) and the newly developed phase-sensitive parametric amplifier (PSA). In an ordinary EDFA, quantum fluctuations are introduced in the course of amplification, resulting in a 3 dB excess noise, whereas in the PSA, no excess noise occurs because the gain is phase-dependent and the noise component having random phase is not amplified. In addition to noise-free amplification, the PSA has the potential to reshape distorted optical pulses whereby their chirped components are attenuated and suppressed. These features enable us to substantially upgrade the transmission capability, i.e. to increase the non-regenerative repeater spacing by as much as 10 times.

Very recently, we succeeded in confirming this mechanism (Imajuku & Takada 1999), and attained the excess noise figure of 2.0 dB, 1 dB lower than the standard quantum limit of 3 dB, at a signal gain of 16 dB. However, the low-loss baseband bandwidth available was confined to only *ca.* 100 MHz. This is due to the guided acoustic wave Brillouin scattering in the low-frequency region (less than 2 GHz) of the nonlinear fibre Sagmnac interferometer (Imajuku & Takada 1999). This technology is still in its infancy, but its impact could be significant.

6. Summary

The envisaged direction of network advancement is summarized below.

(1) Performance enhancement in IP-based multimedia communication is necessary and will be effectively made possible by introducing wavelength routing.

(2) Future networks should gracefully accommodate increasing levels of heterogeneity with regard to traffic conditions, QoS levels, and protocols. This can be effectively attained (Sato & Okamoto 1999) through the use of the abundant network resources of the core network; the emphasis will shift from link use enhancement to QoS enhancement.

(3) The optical layer should have the ability to accommodate different electrical signal formats effectively, and provide layer 1 functions that include the QoS measurement function, essential for developing robust networks.

(4) Maximum commonality with already-established networks is also a crucial issue. The synergy of recent photonic and electrical technologies will create really effective networks.

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